Extremophiles 2017 vol.21 N1, pages 109-120

Genetic background of enhanced radioresistance in an anhydrobiotic insect: transcriptional response to ionizing radiations and desiccation

Ryabova A., Mukae K., Cherkasov A., Cornette R., Shagimardanova E., Sakashita T., Okuda T., Kikawada T., Gusev O.
Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

Abstract

© 2016, Springer Japan.It is assumed that resistance to ionizing radiation, as well as cross-resistance to other abiotic stresses, is a side effect of the evolutionary-based adaptation of anhydrobiotic animals to dehydration stress. Larvae of Polypedilum vanderplanki can withstand prolonged desiccation as well as high doses of ionizing radiation exposure. For a further understanding of the mechanisms of cross-tolerance to both types of stress exposure, we profiled genome-wide mRNA expression patterns using microarray techniques on the chironomid larvae collected at different stages of desiccation and after exposure to two types of ionizing radiation—70 Gy of high-linear energy transfer (LET) ions (4He) and the same dose of low-LET radiation (gamma rays). In expression profiles, a wide transcriptional response to desiccation stress that much exceeded the amount of up-regulated transcripts to irradiation exposure was observed. An extensive group of coincidently up-regulated overlapped transcripts in response to desiccation and ionizing radiation was found. Among this, overlapped set of transcripts was indicated anhydrobiosis-related genes: antioxidants, late embryogenesis abundant (LEA) proteins, and heat-shock proteins. The most overexpressed group was that of protein-L-isoaspartate/D-aspartate O-methyltransferase (PIMT), while probes, corresponding to LEA proteins, were the most represented. Performed functional analysis showed strongly enriched gene ontology terms associated with protein methylation. In addition, active processes of DNA repair were detected. We assume that the cross-tolerance of the sleeping chironomid to both desiccation and irradiation exposure comes from a complex mechanism of adaptation to anhydrobiosis.

http://dx.doi.org/10.1007/s00792-016-0888-9

Keywords

Anhydrobiosis, Bioinformatics and evolutionary relationship of enzymes, Molecular biology, Radiation tolerance

References

[1] Billi D, Friedmann E, Hofer KG, Caiola MG, Ocampo-Friedmann R (2000) Ionizing-radiation resistance in the desiccation-tolerant cyanobacterium Chroococcidiopsis. Appl Environ Microbiol 66(4):1489–1492. doi:10.1128/AEM.66.4.1489-1492.2000

[2] Calahan D, Dunham M, DeSevo C, Koshland DE (2011) Genetic analysis of desiccation tolerance in Sachharomyces cerevisiae. Genetics 189(2):507–519. doi:10.1534/genetics.111.130369

[3] Challabathula D, Puthur JT, Bartels D (2015) Surviving metabolic arrest: photosynthesis during desiccation and rehydration in resurrection plants. Ann N Y Acad Sci 1365(1):89–99. doi:10.1111/nyas.12884

[4] Cornette R, Kikawada T (2011) The induction of anhydrobiosis in the sleeping chironomid: current status of our knowledge. IUBMB Life 63:419–429. doi:10.1002/iub.463

[5] Cornette R, Kanamori Y, Watanabe M, Nakahara Y, Gusev O, Mitsumasu K, Kadono-Okuda K, Shimomura M, Mita K, Kikawada T, Okuda T (2010) Identification of anhydrobiosis-related genes from an expressed sequence tag database in the cryptobiotic midge Polypedilum vanderplanki (Diptera; Chironomidae). J Biol Chem 285(46):35889–35899. doi:10.1074/jbc.M110.150623

[6] Cox MM, Battista JR (2005) Deinococcus radiodurans–the consummate survivor. Nat Rev Microbiol 3(11):882–892. doi:10.1038/nrmicro1264

[7] Cromie GA, Connelly JC, Leach DRF (2001) Recombination at double-strand breaks and DNA ends: conserved mechanisms from phage to humans. Mol Cell 8(6):1163–1174

[8] Crowe LM, Crowe JH (1992) Anhydrobiosis: a strategy for survival. Adv Space Res 12(4):239–247

[9] Desrosiers RR, Fanelus I (2011) Damaged proteins bearing L-isoaspartyl residues and aging: a dynamic equilibrium between generation of isomerized forms and repair by PIMT. Curr Aging Sci 4(1):8–18

[10] Dinakar C, Bartels D (2013) Desiccation tolerance in resurrection plants: new insights from transcriptome, proteome and metabolome analysis. Front Plant Sci 4:482. doi:10.3389/fpls.2013.00482

[11] França MB, Panek AD, Eleutherio EC (2007) Oxidative stress and its effects during dehydration. Comp Biochem Physiol A Mol Integr Physiol 146(4):621–631

[12] Furuchi T, Sakurako K, Katane M, Sekine M, Homma H (2010) The role of protein L-isoaspartyl/D-aspartyl O-methyltransferase (PIMT) in intracellular signal transduction. Chem Biodivers 7(6):1337–1348. doi:10.1002/cbdv.200900273

[13] Gechev TS, Dinakar C, Benina M, Toneva V, Bartels D (2012) Molecular mechanisms of desiccation tolerance in resurrection plants. Cell Mol Life Sci 69(19):3175–3186. doi:10.1007/s00018-012-1088-0

[14] Gladyshev E, Meselson M (2008) Extreme resistance of bdelloid rotifers to ionizing radiation. PNAS 105(13):5139–5144. doi:10.1073/pnas.0800966105

[15] Griffiths CA, Gaff DF, Neale AD (2014) Drying without senescence in resurrection plants. Front Plant Sci 5:36. doi:10.3389/fpls.2014.00036

[16] Gusev O, Nakahara Y, Vanyagina V, Malutina L, Cornette R, Sakashita T, Hamada N, Kikawada T, Kobayashi Y, Okuda T (2010) Anhydrobiosis-associated nuclear DNA damage and repair in the sleeping chironomid: linkage with radioresistance. PLoS One 5(11):e14008. doi:10.1371/journal.pone.0014008

[17] Gusev O, Suetsugu Y, Cornette R, Kawashima T, Logacheva MD, Kondrashov AS, Penin AA, Hatanaka R, Kikuta S, Shimura S, Kanamori H, Katayose Y, Matsumoto T, Shagimardanova E, Alexeev D, Govorun V, Wisecaver J, Mikheyev A, Koyanagi R, Fujie M, Nishiyama T, Shigenobu S, Shibata TF, Golygina V, Hasebe M, Okuda T, Satoh N, Kikawada T (2014) Comparative genome sequencing reveals genomic signature of extreme desiccation tolerance in the anhydrobiotic midge. Nat Commun 5:4784. doi:10.1038/ncomms5784

[18] Halberg KA, Jørgensen A, Møbjerg N (2013) Desiccation tolerance in the tardigrade Richtersius coronifer relies on muscle mediated structural reorganization. PLoS One 8(12):e85091. doi:10.1371/journal.pone.0085091

[19] Hall EJ, Giaccia AJ (2006) Radiobiology for the radiologist, 6th ed. Philadelphia: Lippincott Williams&Wilkins p 546

[20] Han W, Yu PKN (2010) Ionizing radiation, DNA double strand break and mutation. Chapter 7. In: Advances in genetics research, Vol. 4. Nova Science Publishers, Inc., New York

[21] Hand SC, Menze MA (2015) Molecular approaches for improving desiccation tolerance: insights from the brine shrimp Artemia franciscana. Planta 242(2):379–388. doi:10.1007/s00425-015-2281-9

[22] Hengherr S, Heyer AG, Köhler HR, Schill RO (2008) Trehalose and anhydrobiosis in tardigrades–evidence for divergence in responses to dehydration. FEBS J 275(2):281–288

[23] Hengherr S, Worland MR, Reuner A, Brummer F, Schill RO (2009) High-temperature tolerance in anhydrobiotic tardigrades is limited by glass transition. Physiol Biochem Zool 82:749–755. doi:10.1086/605954

[24] Hinton HE (1960) A fly larva that tolerates dehydration and temperatures of −270 °C to +102 °C. Nature 188(4747):336–337. doi:10.1038/188336a0

[25] Hoekstra FA, Golovina EA, Buitink J (2001a) Mechanisms of plant desiccation tolerance. Trends Plant Sci 6(9):431–438. doi:10.1016/S1360-1385(01)02052-0

[26] Hoekstra FA, Golovina EA, Tetteroo FA, Wolkers WF (2001b) Induction of desiccation tolerance in plant somatic embryos: how exclusive is the protective role of sugars? Cryobiology 43(2):140–150

[27] Ito C, Goto SG, Numata H (2013) Desiccation and heat tolerance of eggs of the Asian tadpole shrimp. Triops granarius. Zoolog Sci 30(9):760–766. doi:10.2108/zsj.30.760

[28] Khare S, Linster CL, Clarke SG (2011) The interplay between protein L-isoaspartyl methyltransferase activity and insulin-like signaling to extend lifespan in Caenorhabditis elegans. PLoS One 6(6):e20850. doi:10.1371/journal.pone.0020850

[29] Kikawada T, Minakawa N, Watanabe M, Okuda T (2005) Factors inducing successful anhydrobiosis in the African Chironomid Polypedilum vanderplanki: significance of the larval tubular nest. Integr Comp Biol 45(5):710–714

[30] Kikawada T, Nakahara Y, Kanamori Y, Iwata K-I, Watanabe M, McGee B, Tunnacliffe A, Okuda T (2006) Dehydration-induced expression of LEA proteins in an anhydrobiotic chironomid. Biochem Biophys Res Commun 348(1):56–61. doi:10.1016/j.bbrc.2006.07.003

[31] Koster KL, Leopold AC (1988) Sugars and desiccation tolerance in seeds. Plant Physiol 88(3):829–832

[32] Lapinski J, Tunnacliffe A (2003) Anhydrobiosis without trehalose in bdelloid rotifers. FEBS Lett 553(3):387–390. doi:10.1016/S0014-5793(03)01062-7

[33] Leprince O, Buitink J (2015) Introduction to desiccation biology: from old borders to new frontiers. Planta 242(2):369–378. doi:10.1007/s00425-015-2357-6

[34] Mattimore V, Battista J (1996) Radioresistance of Deinococcus radiodurans: functions necessary to survive ionizing radiation are also necessary to survive prolonged desiccation. J Bacteriol 178:633–637

[35] McGill LM, Shannon AJ, Pisani D, Félix MA, Ramløv H, Dix I, Wharton DA, Burnell AM (2015) Anhydrobiosis and freezing-tolerance: adaptations that facilitate the establishment of Panagrolaimus nematodes in polar habitats. PLoS One 10(3):e0116084. doi:10.1371/journal.pone.0116084

[36] Moskalev A, Zhikrivetskaya S, Krasnov G, Shaposhnikov M, Proshkina E, Borisoglebsky D, Danilov A, Peregudova D, Sharapova I, Dobrovolskaya E, Solovev I, Zemskaya N, Shilova L, Snezhkina A, Kudryavtseva A (2015) A comparison of the transcriptome of Drosophila melanogaster in response to entomopathogenic fungus, ionizing radiation, starvation and cold shock. BMC Genom 16(Suppl 13):S8. doi:10.1186/1471-2164--6-S13-S8

[37] Musilova M, Wright G, Ward JM, Dartnell LR (2015) Isolation of radiation-resistant bacteria from Mars analog Antarctic dry valleys by preselection, and the correlation between radiation and desiccation resistance. Astrobiology 15(12):1076–1090. doi:10.1089/ast.2014.1278

[38] Potts M, Slaughter SM, Hunneke FU, Garst JF, Helm RF (2005) Desiccation tolerance of prokaryotes: application of principles to human cells. Integr Comp Biol 45(5):800–809. doi:10.1093/icb/45.5.800

[39] Rebecchi L, Altiero T, Guidetti R (2007) Anhydrobiosis: the extreme limit of desiccation tolerance. ISJ 4:65–81

[40] Schmitt FJ, Renger G, Friedrich T, Kreslavski VD, Zharmukhamedov SK, Los DA, Kuznetsov VV, Allakhverdiev SI (2014) Reactive oxygen species: re-evaluation of generation, monitoring and role in stress-signaling in phototrophic organisms. Biochim Biophys Acta 1837(6):835–848. doi:10.1016/j.bbabio.2014.02.005

[41] Shapiro-Ilan DI, Brown I, Lewis EE (2014) Freezing and desiccation tolerance in entomopathogenic nematodes: diversity and correlation of traits. J Nematol 46(1):27–34

[42] Shen-Miller J, Mudgett MB, Schopf JW, Clarke S, Berger R (1995) Exceptional seed longevity and robust growth: ancient sacred lotus from China. Am J Bot 82(11):1367–1380. doi:10.2307/2445863

[43] Somme L (1996) Anhydrobiosis and cold tolerance in tardigrades. Eur J Entomol 93(3):349–357

[44] Tanaka M, Earl AM, Howell HA, Park MJ, Eisen JA, Peterson SN, Battista JR (2004) Analysis of Deinococcus radiodurans's transcriptional response to ionizing radiation and desiccation reveals novel proteins that contribute to extreme radioresistance. Genetics 168:21–33. doi:10.1534/genetics.104.029249

[45] Watanabe M (2006) Anhydrobiosis in invertebrates. Appl Entomol Zool 41(1):15–31. doi:10.1303/aez.2006.15

[46] Watanabe M, Kikawada T, Minagawa N, Yukuhiro F, Okuda T (2002) Mechanism allowing an insect to survive complete dehydration and extreme temperatures. J Exp Biol 205:2799–2802

[47] Watanabe M, Kikawada T, Okuda T (2003) Increase of internal ion concentration triggers trehalose synthesis associated with cryptobiosis in larvae of Polypedilum vanderplanki. J Exp Biol 206:2281–2286

[48] Watanabe M, Sakashita T, Fujita A, Kikawada T, Horikawa DD et al (2006a) Biological effects of anhydrobiosis in an African chironomid, Polypedilum vanderplanki on radiation tolerance. Int J Radiat Biol 82:587–592

[49] Watanabe M, Sakashita T, Fujita A, Kikawada T, Nakahara Y et al (2006b) Estimation of radiation tolerance to high LET heavy ions in an anhydrobiotic insect, Polypedilum vanderplanki. Int J Radiat Biol 82:835–842

[50] Watanabe M, Nakahara Y, Sakashita T, Kikawada T, Fujita A, Hamada N, Horikawa DD, Wada S, Kobayashi Y, Okuda T (2007) Physiological changes leading to anhydrobiosis improve radiation tolerance in Polypedilum vanderplanki larvae. J Insect Physiol 53(6):573–579

[51] Yoshinaga K, Yoshioka H, Kurosaki H, Hirasawa K, Uritani M, Hasegawa M (1997) Protection by trehalose of DNA from radiation damage. Biosci Biotechnol Biochem 61(1):160–161